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LATE-STAGE EQUIVALENCE IN ONE-DIMENSIONAL IMPACTS

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ABSTRACT

The attenuation of a strong plane shock produced in a target by the impact of a thin striker is studied by the numerical method of characteristics. The calculated results show that late-stage equivalence exists for impacts in aluminum, copper, and ideal gases with various ratios of specific heats, γ. The shock fronts produced by different impacts approach each other in position, and in strength, at late times provided that du_o^{α} is constant where d is the thickness of the striker, u_o the impact velocity, and α a constant with values of 1.28, 1.50, 1.62, 1.50, and 1.32, for aluminum, copper, and ideal gases with γ equal to 2.0, 1.4, and 1.1, respectively.

LIST OF FIGURES

SYMBOLS

A - area

c - sound speed

d - striker plate thickness

E - specific internal energy

F - friction force

p - pressure

q - heat transfer rate per unit time and per unit mass

s - specific entropy

t - time variable

u - particle velocity

U - shock wave velocity

x - space variable

α - equivalence parameter

γ - ratio of specific heats

ν - geometric parameter

ρ - density

Subscripts

o - initial condition

x - conditions just ahead of a shock

y - conditions just behind a shock

I. INTRODUCTION

In Reference 1, the problem of the attenuation of a strong plane shock produced in aluminum by the impact of a thin striker was studied by three approaches, namely, a graphical method, an approximate analytical method, and experimental observations. Results from these three showed general agreement; and a principle of late-stage equivalence was found to exist. The problem treated consists of the impact of a thin striker plate on a thick target of the same material. Two plane shock waves are produced, one propagating back into the striker and the other propagating forward into the target. Upon reaching the rear surface of the plate, the shock in the striker reflects into a centered rarefaction wave, which eventually overtakes the forward moving shock, and reduces its velocity. The solutions for impacts with strikers of different thickness are shown to exhibit late-stage equivalence provided the thicknesses d and the velocities u_o of the striker are chosen in such a way that $u_o^{\alpha}d$ is a constant with $\alpha = 1.27$. Late-stage equivalence is assumed to exist if the position of the shock front in the (x,t) plane, as well as the peak pressure distribution in the target, for different impacts are the same.

The approximate analytical solution of Ref. 1, which is based on the assumption that the forward-facing characterisitcs are straight lines, is accurate only within a certain time after impact; and is not accurate at very late stage. The graphical solution and experimental results reported in Ref. 1 are also limited to rather short time intervals after impact.

In the present paper, the impact problem is calculated numerically on a computer following the method of characteristics. The results, which are believed to be accurate up to a very late time, indicate that late-stage equivalence exists for ideal gases, for copper, as well as for aluminum. The equivalence parameter α has values of 1.28, 1.50, 1.62, 1.50, and 1.32, for aluminum, copper, ideal gas with $\gamma = 2.0$, 1.4, and 1.1, respectively.

The method of characteristics for one-dimensional unsteady flow is quite well-known, especially if the medium is an ideal gas and the solution is intended by hand calculation or by graphical means.[2] Recently, Hoskin[3] presented the characteristic equations in Lagrangian coordinates and the procedures for computer calculation. In the following section, we shall first present the governing characteristic equations in Eulerian coordinates for any perfect fluid with a known equation of state. The subsequent numerical procedure is also designed for computer calculation.

II. GOVERNING EQUATIONS

The equations are written in terms of four dependent variables ρ, u, p, and E, because most equations of state are given in the form of one relation between p, ρ, and E. The friction and heat addition effects are included in the derivation for general reference.

The governing equations for one-dimensional unsteady motions of a perfect fluid are the conservation of mass equation

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u}{\partial x} + u \frac{\partial \rho}{\partial x} = \frac{-\rho u}{A} \frac{dA}{dx} \qquad (1)$$

the conservation of momentum equation

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \left(\frac{\partial p}{\partial E}\right)_\rho \frac{\partial E}{\partial x} + \frac{1}{\rho} \left(\frac{\partial p}{\partial \rho}\right)_E \frac{\partial \rho}{\partial x} = -F \tag{2}$$

and the conservation of energy equation

$$\frac{\partial E}{\partial t} + u \frac{\partial E}{\partial x} - \frac{p}{\rho^2} \frac{\partial \rho}{\partial t} - \frac{pu}{\rho^2} \frac{\partial \rho}{\partial x} = q + uF \tag{3}$$

where u is the particle velocity; ρ, the density; p, the pressure; E, the specific internal energy; A, the area; q, the heat addition; and F, the frictional force per unit mass of fluid. In addition to (1) to (3), we shall assume that an equation of state of the form

$$p = p(E, \rho) \tag{4}$$

exists; therefore

$$dp = \left(\frac{\partial p}{\partial E}\right)_\rho dE + \left(\frac{\partial p}{\partial \rho}\right)_E d\rho \tag{5}$$

In regions where the properties u, ρ, and E are continuous, three equations of total differentials may be written, i.e.,

$$\begin{aligned} du &= \frac{\partial u}{\partial x} dx + \frac{\partial u}{\partial t} dt \\ d\rho &= \frac{\partial \rho}{\partial x} dx + \frac{\partial \rho}{\partial t} dt \\ dE &= \frac{\partial E}{\partial x} dx + \frac{\partial E}{\partial t} dt \end{aligned} \tag{6}$$

From the six equations (1) to (3) and (6), the six first derivatives of u, ρ, and E, may be solved for and arranged in a quotient form, such as,

$$\frac{\partial \rho}{\partial x} = \frac{N}{D} \tag{7}$$

The vanishing of the denominator D yields three physical characteristics

$$\left(\frac{dx}{dt}\right)_{I,II} = u \pm \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_E + \frac{p}{\rho^2}\left(\frac{\partial p}{\partial E}\right)_\rho} \qquad (8)$$

$$\left(\frac{dx}{dt}\right)_{III} = u \qquad (9)$$

where the I and II characteristics are the right traveling and left traveling Mach waves, and the III characteristics are particle path lines. Introducing the sound speed, c, defined by

$$c^2 = \left(\frac{\partial p}{\partial \rho}\right)_s \qquad (10)$$

where the derivative is taken at constant entropy, s; and keeping in mind the thermodynamic relationship

$$T\,ds = dE - \frac{p}{\rho^2}d\rho \qquad (11)$$

it may be shown that

$$c^2 = \left(\frac{\partial p}{\partial \rho}\right)_E + \frac{p}{\rho^2}\left(\frac{\partial p}{\partial E}\right)_\rho \qquad (12)$$

Thus, Eqs. (8) become

$$\left(\frac{dx}{dt}\right)_{I,II} = u \pm c \qquad (13)$$

The vanishing of N in Eq. (7) yields, after utilizing Eqs. (5) and (12), the state characteristics

$$\frac{dp}{\rho c} \pm du + dt\left[\pm F - \left(\frac{\partial p}{\partial E}\right)_\rho \frac{1}{\rho c}(q + uF) + \frac{uc}{A}\frac{dA}{dx}\right] = 0 \qquad (14)$$

along the I-characteristics (upper signs) and II-characteristics (lower signs), respectively; and

$$\frac{p}{\rho^2}d\rho - dE + (q + uF)dt = 0 \qquad (15)$$

along the III-characteristics.

Equations (14) and (15), together with Eqs. (5) and (12), govern the variables p, ρ, u, E, and c, along the characteristic directions. The terms $(1/A)(dA/dx)$ assumes the form $(\nu-1)/x$, where ν has the value of 1, 2, or 3 for plane, cylindrical, or spherical symmetrical flow, respectively.

For ideal gas with an equation of state

$$p = (\gamma - 1) E\rho \tag{16}$$

where γ is the ratio of specific heat , Eqs. (14) and (15) reduce to

$$\frac{dp}{\rho c} \pm du + dt \left[\pm F - (\gamma-1) \frac{1}{c} (q+uF) + \frac{uc}{A} \frac{dA}{dx} \right] = 0 \tag{17}$$

along I and II; and

$$d\rho = \frac{1}{c^2} \left[dp - (\gamma-1) \rho (q+uF) dt \right] \tag{18}$$

along III.

Across a shock, the conservation of mass, momentum and energy leads to the following familiar equations:

$$\rho_y(U-u_y) = \rho_x(U-u_x) \tag{19}$$

$$p_y - p_x = \rho_x(U-u_x)(u_y-u_x) \tag{20}$$

$$p_y u_y - p_x u_x = \rho_x(U-u_x) \left[E_y - E_x + \frac{1}{2}(u_y^2 - u_x^2) \right] \tag{21}$$

where U is the shock velocity, and subscripts x and y refer to states ahead of and behind the shock front, respectively. If all properties ahead of the shock are known, then the quantities p_y, ρ_y, u_y, E_y, and U are related by the four equations, (4) and (19) to (21). Specification of any one of these variables will determine the remaining ones. For most solids under high pressure the available equation of state as expressed in the form of Eq. (4) is often semiempirical with uncertain

accuracy. On the other hand, more accurate shock Hugoniot data are available for most solids through direct measurements. This shock Hugoniot may be conveniently expressed as a relation between the pressure and density behind the shock for a given condition ahead of it, or,

$$p_y = p_y(\rho_y) \tag{22}$$

This shock Hugoniot, instead of the general equation of state, Eq. (4), may be used for shock fronts. Thus Eqs. (19), (20), and (22) govern the four variables p_y, ρ_y, U, and u_y; specification of any one of these will determine the other three.

In performing the numerical calculation, the characteristics equations, (13), (14), and (15) are written in finite-difference form, similar to those used in Ref. 4. For the present impact problem, we assume that q, F, and dA all vanish.

III. NUMERICAL TECHNIQUE

A typical impact problem is demonstrated in Fig. 1, which shows the physical plane of the decay of the shock front and the flow field behind it. The distance, x, is measured from the free surface of the striker plate at the instant of impact. The properties in regions 0, 1, 2, and 3 are either given, or may be calculated from simple formulas.[1] The properties in region 5, which is bounded by the reflected head of the rarefaction wave BC, the tail of the rarefaction CE, and the shock front BD, are to be calculated by the method of characteristics. The rarefaction wave is divided into one hundred segments along BC, and the properties at each of the dividing points are calculated from the given

initial data and the formula for the simple wave ABC. A characteristic network is then constructed from these points, and the properties at the mesh points of this network are calculated by an iterative process. Two types of points are encountered: the regular interior points and the points on the shock front. For a typical interior point, such as point 3 in Fig. 2, the iteration process is as follows. Assuming all properties at points 1 and 2 are known, a first estimation of the properties at point 3 is made. Physical characteristics from the two known points 1 and 2 are constructed; point 3 is thus located. With an estimated value of u at point A, the intersection between the III-characteristic from point 3 and the straight line joining points 1 and 2, the location of A may be determined. The properties, E, ρ, p, and c, at point A are then obtained by interpolation from those at 1 and 2. More accurate values of properties at point 3 may now be calculated from the finite-difference equations obtained from Eqs. (14) and (15), and Eqs. (5) and (12). This iterative process is repeated until the differences of u, p, and c at point 3 from two successive iterations are below a desired limit. A similar procedure was adopted for points on the shock front. This complete numerical iterative process is an extension of that present in Ref. 4, which can be used for ideal gas only.

IV. RESULTS

Calculations of the impact problem were made for five different materials, namely, aluminum, copper, and ideal gas with values of the ratio of specific heat, γ, equal to 1.1, 1.4, and 2.0. For aluminum

and copper, an equation of state of the following form was used,[5]

$$p = \left(a + \frac{b}{\frac{E}{E_o \eta^2} + 1}\right) E\rho + A\mu + B\mu^2 \tag{23}$$

where $\eta = \rho/\rho_o$ and $\mu = \eta - 1$. The constants used are listed in Table I.

	a	b	A(Mbar)	B(Mbar)	$E_o(\frac{\text{Mbar-cm}^3}{\text{gr}})$
Aluminum	0.5	1.63	0.752	0.65	0.05
Copper	0.5	1.5	1.39	1.1	0.325

Table I Constants Used in the Equations of State for Aluminum and Copper

For each material, a standard impact case was first calculated. Other cases with the same equation of state, the same initial density and sound speed, but different initial velocity and striker plate thickness, were then calculated and results compared with the standard one. The initial condition for the five different materials are shown in Table II.

		u_o(km/sec)	d	p_o(bar)	c_o(km/sec)
	$\gamma = 2.0$	4.572	9.723 cm	1.013	.3048
Ideal Gas	$\gamma = 1.4$	4.572	9.385 cm	1.013	.3048
	$\gamma = 1.1$	4.572	8.900 cm	1.013	.3048
Aluminum		20.33	4.830 mm	1.013	5.275
Copper		22.017	2.885 mm	1.013	3.951

Table II Initial Conditions of the Standard Impact Case for Five Different Materials

The criterion used for late-stage equivalence is the position of the shock front and the peak pressure distribution in the target. Late-stage equivalence is assumed to exist if the position of the shock front in the (x,t) plane, as well as the peak pressure distribution for different impacts are the same.

For each material, impact cases with different combinations of d and u_o are compared with the standard case; yielding a value of α for each case by the relation

$$d_{std} (u_{o\ std})^{\alpha} = d\, u_o^{\alpha} \qquad (24)$$

Figure 3a shows the results of peak pressure distribution for the ideal gas with $\gamma = 1.4$. Figure 3b is a plot of a portion of the pressure distribution curves at an enlarged scale. It can be seen that the peak pressure of all impact cases with $\alpha = 1.5$ are close together at large x, or late time; while those with a value of α different from 1.5 show considerable deviation. Figure 3c gives the corresponding shock front positions, again indicating that cases with $\alpha = 1.5$ are equivalent at late stage. Thus we conclude that for an ideal gas with $\gamma = 1.4$, late-stage equivalence exists for impacts having $\alpha \approx 1.5$, where α is defined in Eq. (24).

For ideal gas with $\gamma = 2$ and 1.1, the late-stage equivalence parameter α assumes values of 1.62 and 1.3, respectively. These results are in agreement with those obtained by Dienes.[6] For aluminum and copper, the values for α are 1.28 and 1.50, respectively, as shown in Figs. 4 and 5.

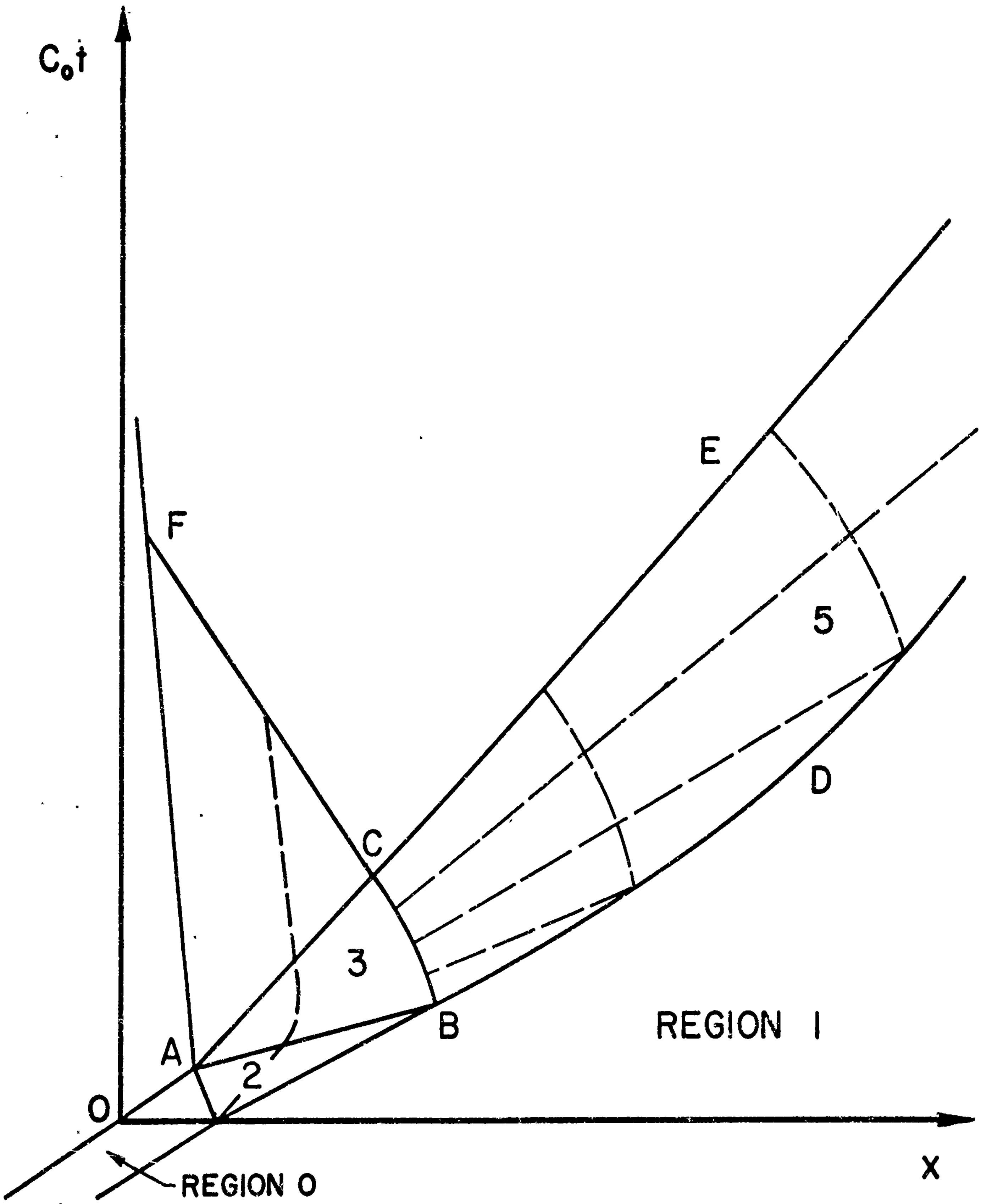

Figure 1 The physical (x,t) plane of one-dimensional impact of a thin striker plate on a semi-infinite target. Properties in regions 0, 1, 2, and 3 are known, and those in region 5 are to be calculated by the method of characteristics.

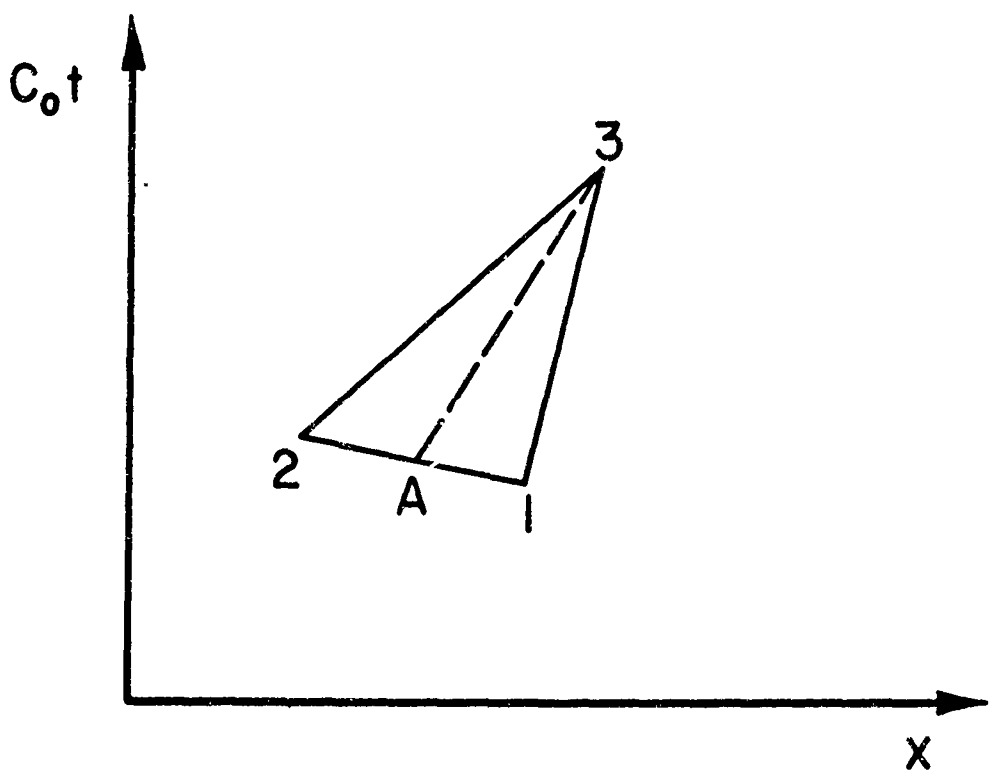

Figure 2 A Typical Interior Point in the (x,t) Plane.

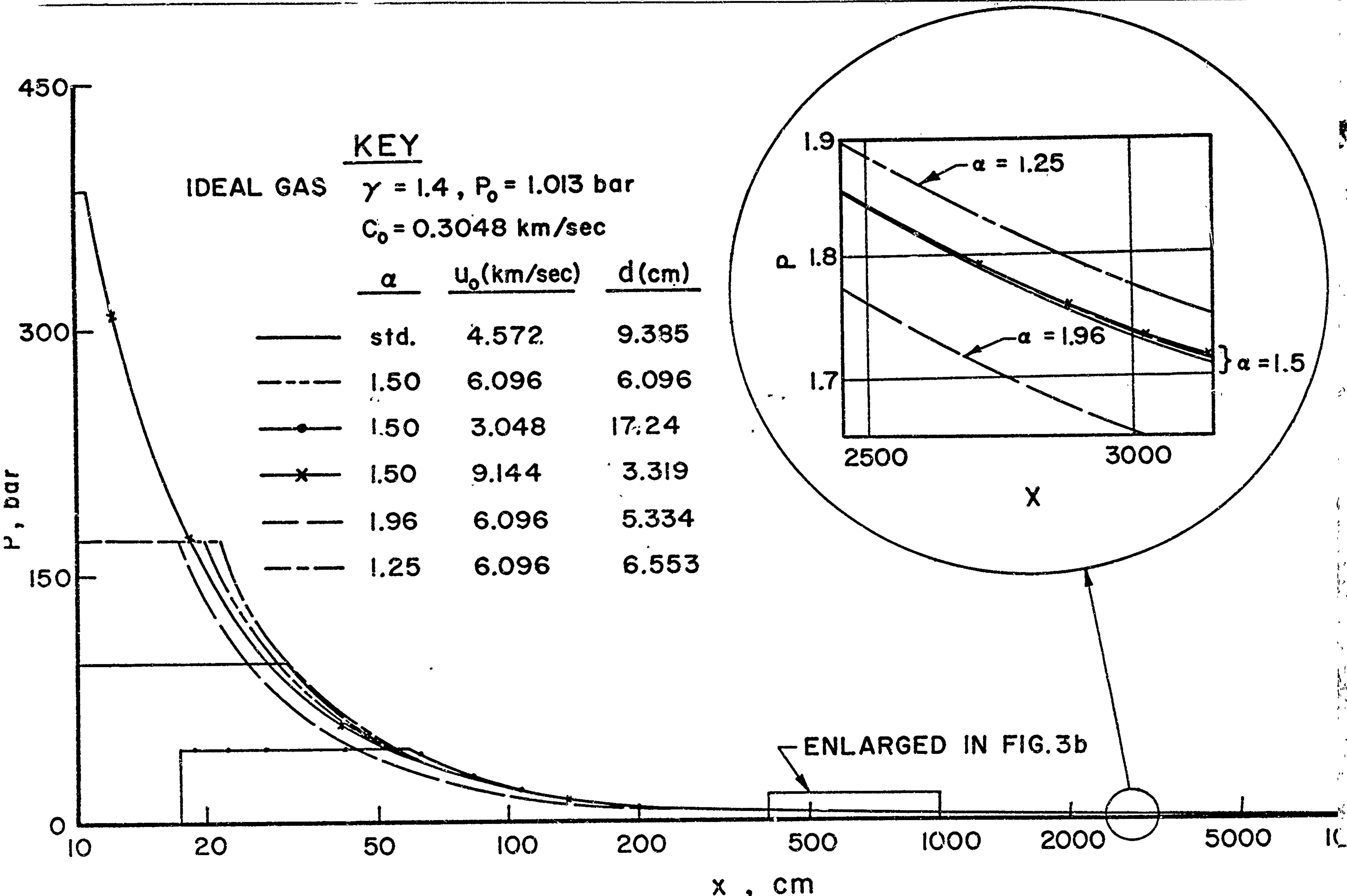

Figure 3 The attenuation of the shock front produced by impacts on ideal gas, γ = 1.4. Late-stage equivalence exists for those impacts having the same values of $du_o^{1.5}$.
(a) Peak pressure vs. distance from the free surface at impact.

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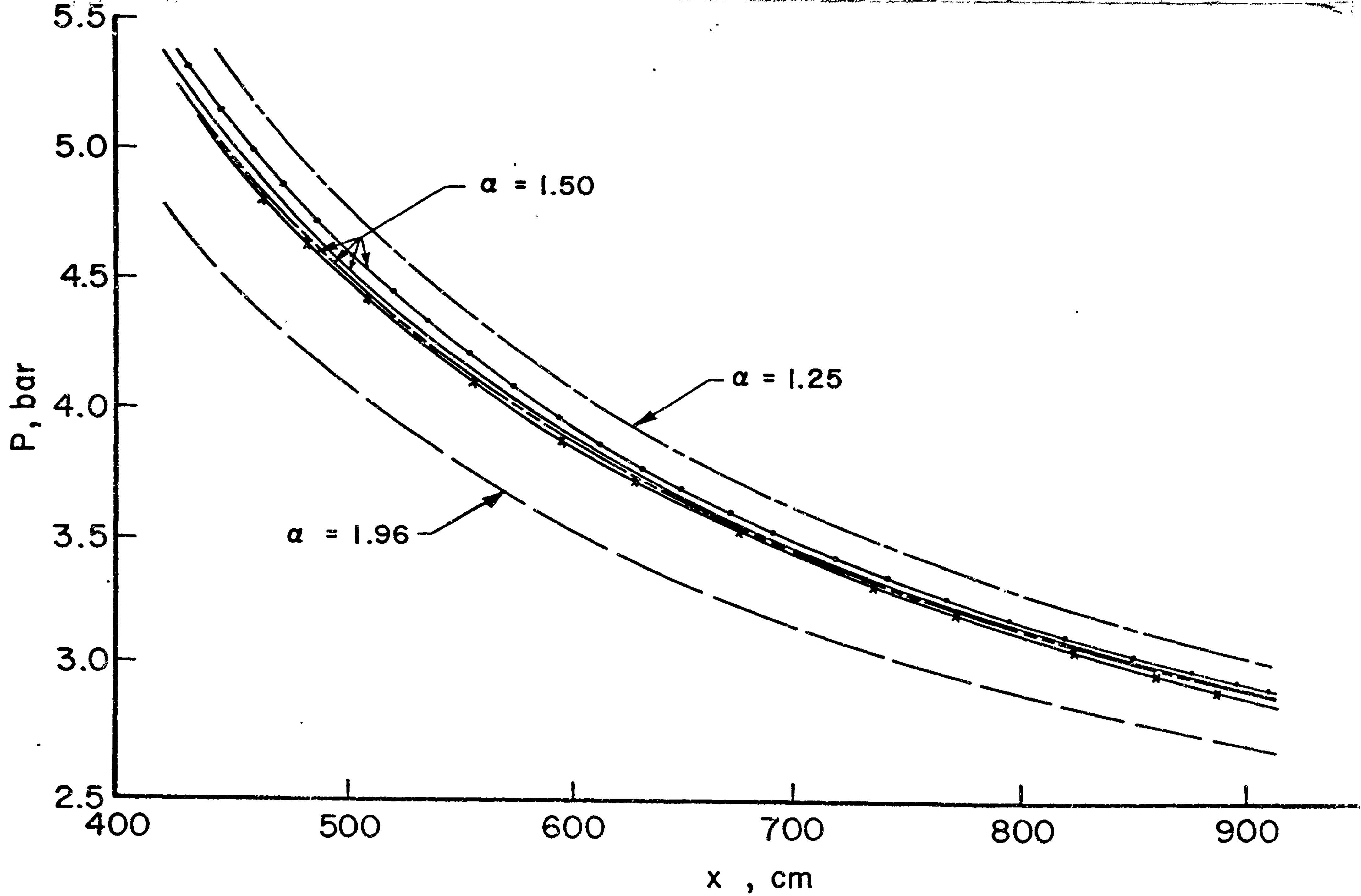

Figure 3 The attenuation of the shock front produced by impacts on ideal gas, $\gamma = 1.4$. Late-stage equivalence exists for those impacts having the same value of $du_o^{1.5}$.
(b) Enlarged region of the peak pressure vs. distance from the free surface at impact.

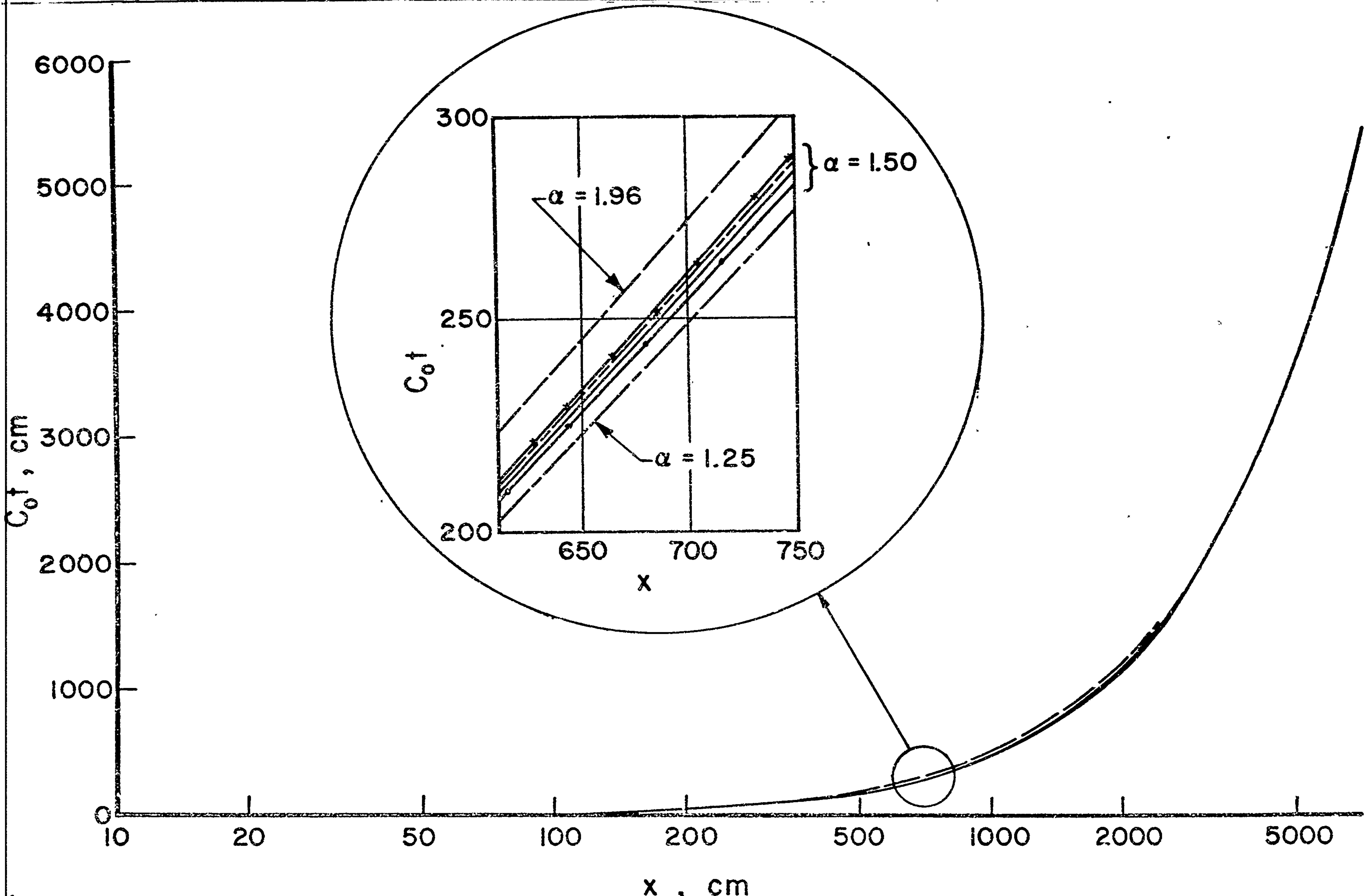

Figure 3 The attenuation of the shock front produced by impacts on ideal gas, $\gamma = 1.4$. Late-stage equivalence exists for those impacts having the same value of $du_o^{1.5}$.
(c) The shock front position

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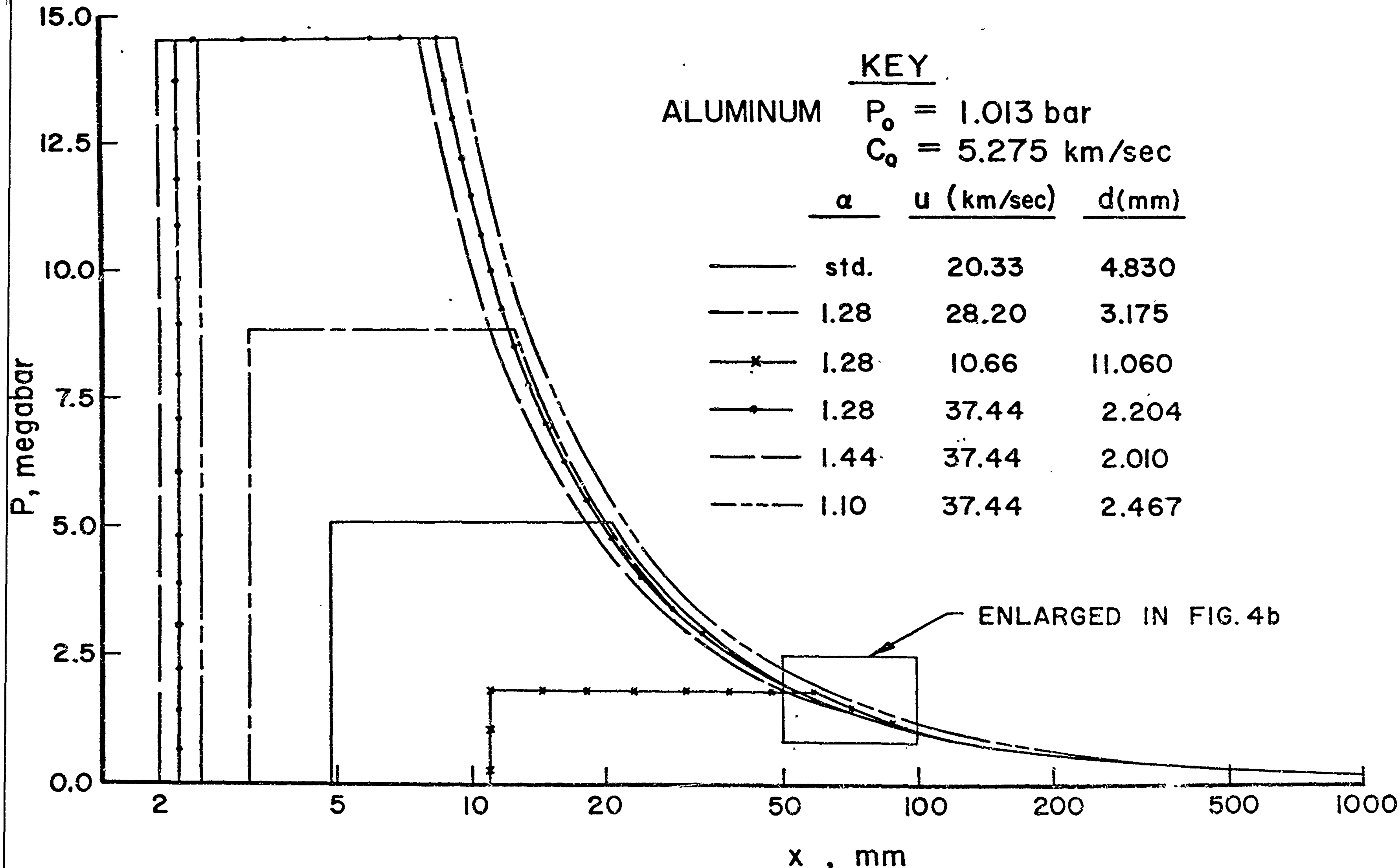

Figure 4 The attenuation of the shock front produced by impacts of aluminum. Late-stage equivalence exists for those impacts having the same value of $du^{1.28}$.
(a) Peak pressure vs. distance from the free surface of impact.

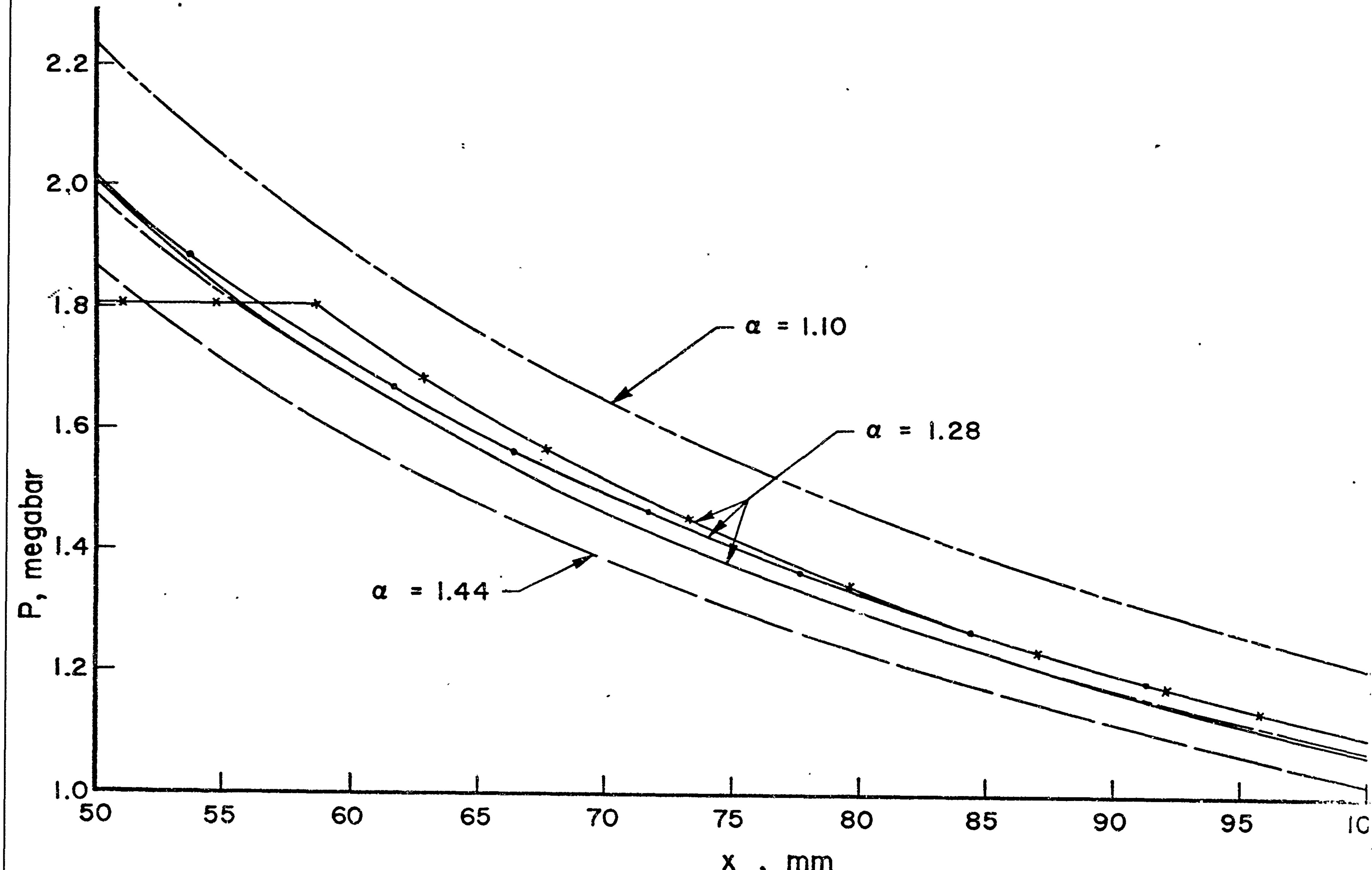

Figure 4 The attenuation of the shock front produced by impacts on aluminum. Late-stage equivalence exists for those impacts having the same value of du 1.28.
(b) Enlarged region of the peak pressure vs. distance from the free surface at impact.

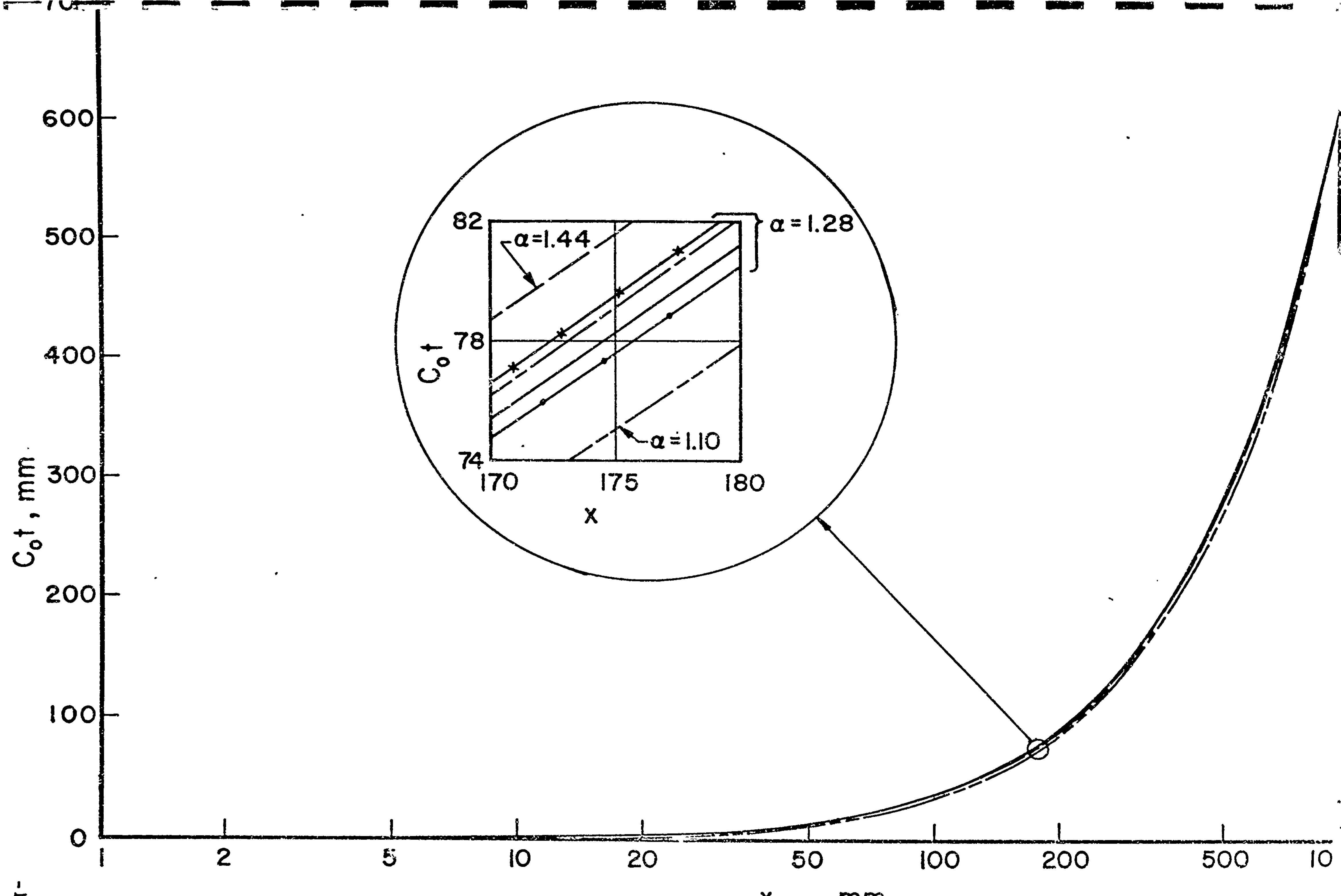

Figure 4 The attenuation of the shock front produced by impacts on aluminum. Late-stage equivalence exists for those impacts having the same value of $du_o^{1.28}$.
(c) The shock front position.

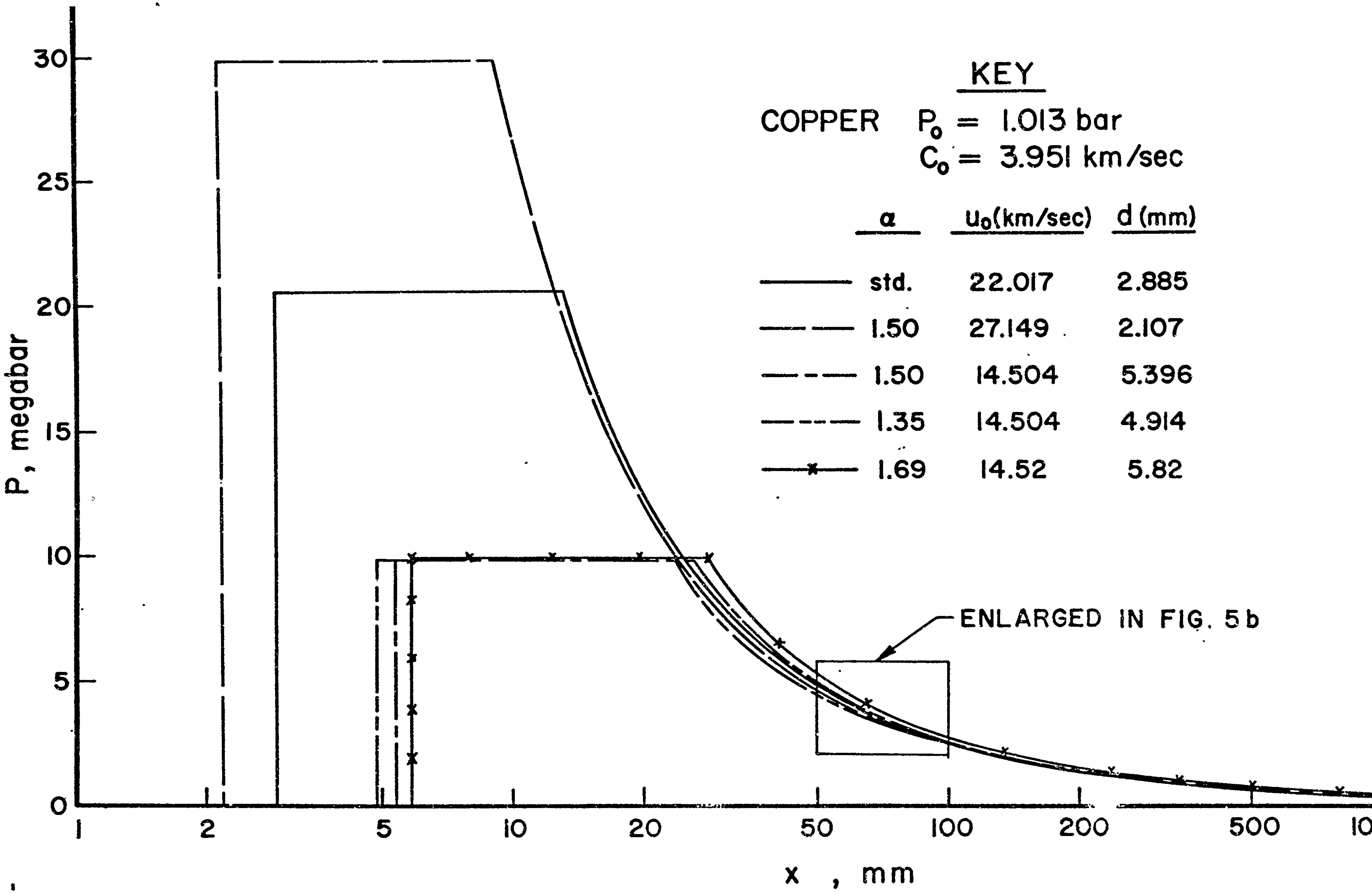

Figure 5 The attenuation of the shock front produced by impacts on copper. Late-stage equivalence exists for those impacts having the same value of $du_o^{1.5}$.
(a) Peak pressure vs. distance from the free surface at impact.

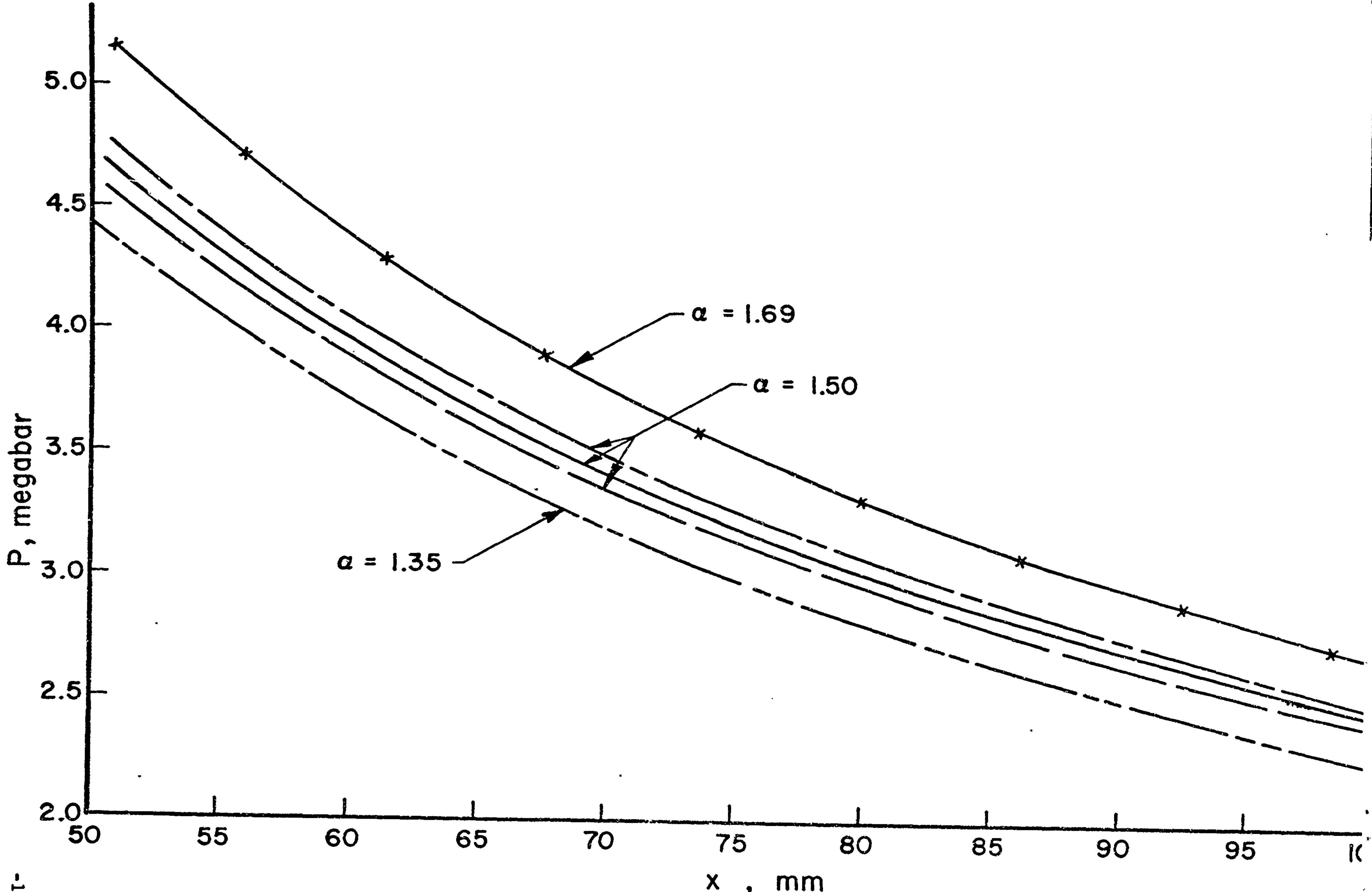

Figure 5 The attenuation of the shock front produced by impacts on copper. Late-stage equivalence exists for those impacts having the same value of du 1.5.
(b) Enlarged region of the peak pressure vs. distance from the free surface at impact.

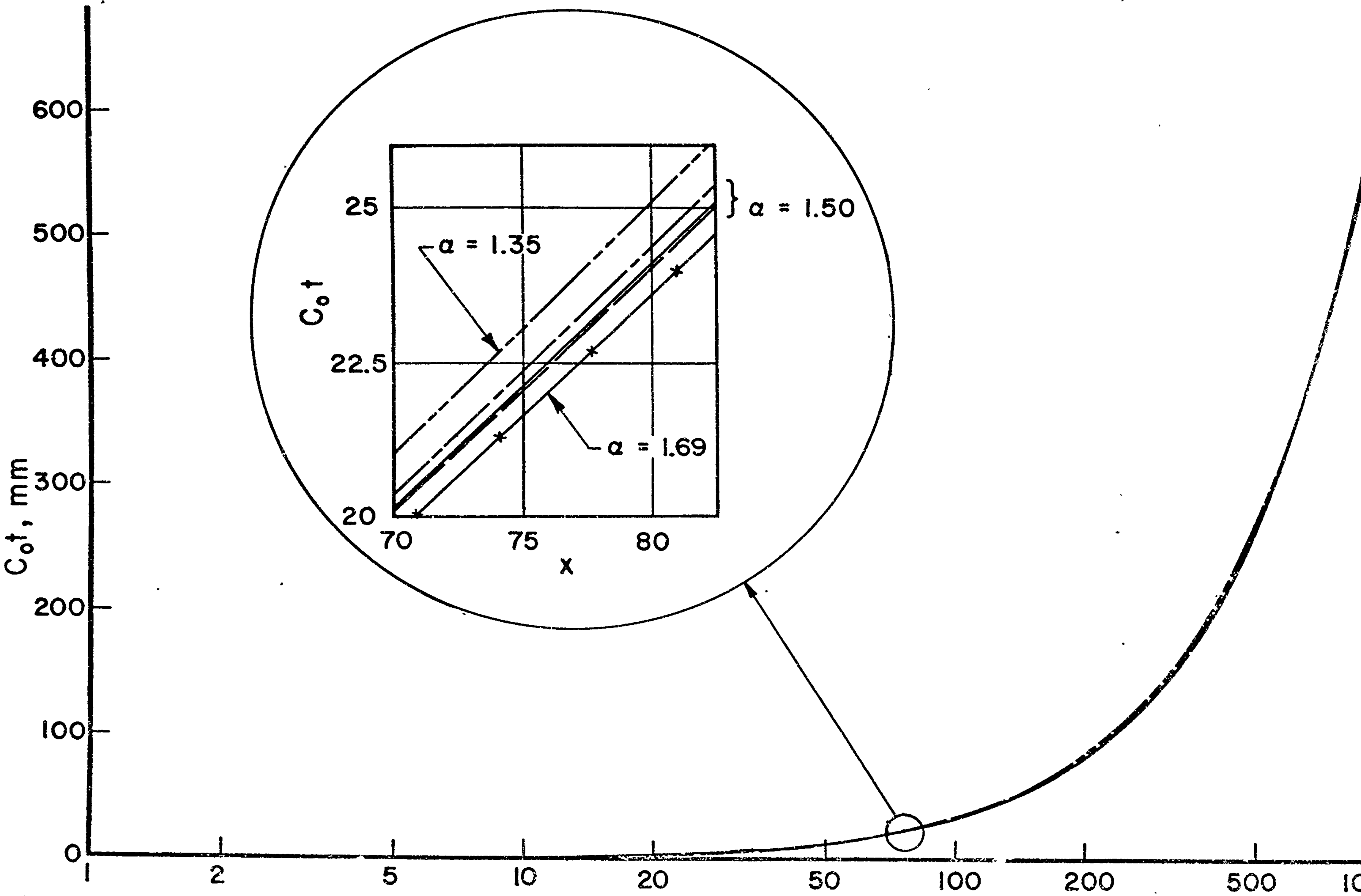

Figure 5 The attenuation of the shock front produced by impacts on copper. Late-stage equivalence exists for those impacts having the same value of $du_o^{1.5}$.
(c) The shock front position.

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